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A CONTROL-CONFIGURED END EFFECTOR FOR A VISUAL SERVOING ALGORITHM

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ABSTRACT

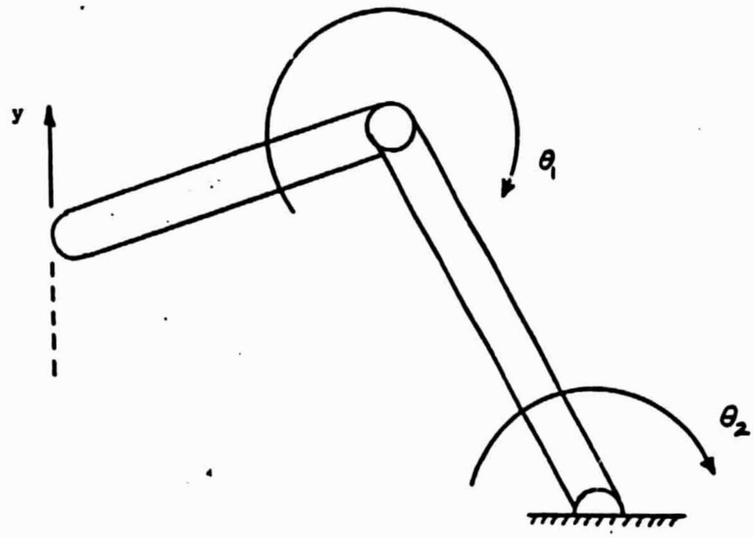
An algorithm is presented for using a robot system with a single camera to position in three-dimensional space a slender object for insertion into a hole; for example, an electrical pin-type termination into a connector hole. The algorithm relies on a control-configured end effector to achieve the required horizontal translations and rotational motion, and it does not require camera calibration. A force sensor in each fingertip is integrated with the vision system to allow the robot to teach itself new reference points when different connectors and pins are used. Variability in the grasped orientation and position of the pin can be accomodated with the sensor system. Performance tests show that the system is feasible. More work is needed to determine more precisely the effects of lighting levels and lighting direction.

1.0 INTRODUCTION

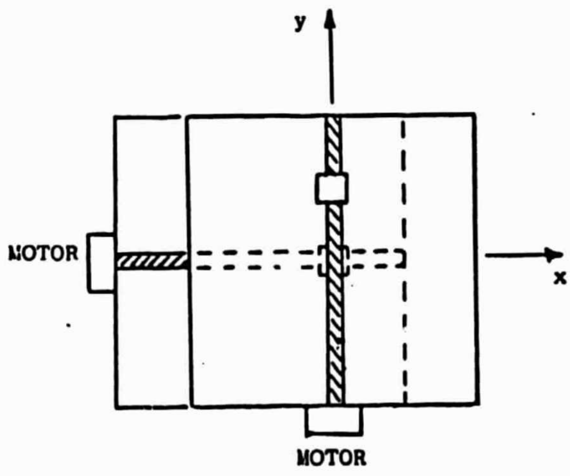
Control engineers frequently are faced with the problem of controlling a device to perform a task for which it is not particularly well-suited. A simple example of this is the two-link robot arm shown in Figure 1(a). In order to obtain straight-line motion of the endpoint in the y-direction, the motors at the two joints must properly control the angles θ_1 and θ_2. This is a nonlinear problem both kinematically and dynamically [1, Chapter 6], [2, Section 9.1]. Also, the coupling between the links means that both motors must perform accurately even though straight-line motion is desired in only one direction. Of course, there are reasons for using such a two-link arrangement, for example, to achieve a large workspace.

However, suppose that we require straight-line motion only over a relatively short distance in the workspace. An easily-controlled device for doing this is known as an xy-translation table, and is shown in Figure 1(b). It consists of two perpendicular lead screws with motors. One screw unit is mounted on a plate, which is in turn mounted to the second screw unit. Suppose we attach the plate to the endpoint of the two-link arm, and the other screw's nut to a gripper. Then we could easily obtain straight-line motion for the gripper by driving the motors in a fixed speed ratio. Note also that if pure translation is desired in either the y or the x direction, then the motion error is due to only one of the motors, and is not cumulative.

Devices or systems like the one in Figure 1(b) that are designed from the start with ease of control in mind are said to be control-configured. As modern systems become more complex, their control becomes more difficult, and it is important that they be control-configured early in the design process. This is especially true



(a)



(b)

Figure 1. Achieving Straight-Line Motion. (a) The two-link manipulator has nonlinear kinematics. (b) The platform-lead screw mechanism has linear kinematics.

in robotic systems, where complex kinematic relationships are quite common. In addition to choosing kinematic arrangements that are easily controlled, a system can also be control-configured by proper sensor integration; that is, proper choice of sensor locations and sensor types to complement each other's capabilities and to satisfy the needs of the control algorithm.

In this paper we discuss a visual servoing algorithm and the design of a control-configured robotic end effector to implement that algorithm. The algorithm uses a single camera to guide the end effector in positioning the workpiece. Only two-dimensional information is available from a single stationary camera. However, with the proper control strategy and sensor integration, positioning in the three-dimensional space can be accomplished. The control algorithm to be presented integrates the camera information with feedback from a force sensor on the end effector to position a slender object for insertion into a hole.

There has been much published on the "peg-in-hole" insertion problem. This can be a difficult problem where tolerances are tight, and the success rate can be improved by the use of a remote-center compliance (RCC) device. However, in our application, the insertion process is not difficult because the tolerances are large and because of the inherent compliance in the fingertips of the end effector. In this paper we are concerned primarily with the positioning process necessary to align the workpiece above the hole prior to insertion.

Few general methods are available for the design of control-configured end effectors. Palm [3] discusses the control of a non-anthropomorphic hand configuration for manipulating cylindrical objects in five degrees of freedom. The hand is easy to control because

the motion of each degree of freedom can be produced without requiring complicated coordination of more than one motor. Some kinematic and control principles useful for the design of control-configured hands are given by Datseris [4].

2.0 CONTROL FOR ASSEMBLY APPLICATIONS

Assembly operations for products that change slightly from one model to another cannot be performed utilizing fixed automation techniques. One such problem is the assembly of electronic wire harnesses. Small quantities of each type of wire harness are assembled at one time, and each wire harness may consist of different types of components and wires. The development of a flexible system for the insertion of electrical pins into a connector would offer a partial solution to automating the assembly. Although motivated by the wire harness application, the results to be presented are generic enough to be applicable to the general problem of using a single camera to position an object.

A programmable robot is a vital part of the assembly operation due to the flexibility required by the operation. A robot like the PUMA series 560/600 has good repeatability but is less accurate when trying to position at a calculated point. Accuracy is then only achieved by teaching the point to the robot. This operation decreases the flexibility of the system unless sensors can be used to allow the robot to teach itself the required reference points as new situations arise. The results presented here make use of vision and force sensors to give the robot this capability.

We have used the following wire harness assembly scenario in developing the results. In order to avoid the need for manual setup, one or more robots place the connectors in fixtures and also route the

wires. The fixtures hold the connectors firmly throughout the operation. Thus the robot knows the general location of each connector but there may be some uncertainty in the rotational orientation of the connector and in the height of the connector's surface. By means of a registration mark on the connector it is possible to use machine vision techniques to approximately locate the ordered holes in the connector [5]. But since these are calculated points the robot will have some positional inaccuracies unless it can automatically teach itself a reference point on the connector. Once this has been done the robot can begin inserting wires with pin-type terminations into the proper holes. In this paper we focus on the algorithms required to teach the reference point and to visually servo the pin to the imprecisely-known hole location.

After several wires have been inserted into the connector, it becomes impossible to use any visual servoing technique to find the holes. However, once the first two holes are located by the method to be presented, the angular orientation of the connector in the horizontal plane is known. Therefore the locations of the holes can be supplied to the robot from the geometric data base for the connector. Because the holes are relatively close together, there will be negligible error in moving to them even though they are calculated points.

There have been other investigations of the use of visual servoing for assembly applications. For example, Agin [6] and Berger [7] discuss geometries similar to the one to be presented here, but they use a camera attached to the end effector. This arrangement presents other difficulties. Others are investigating the use of two cameras for stereoscopic vision. But little is known about the effective use of a single camera integrated with other sensors to produce a system capable

of automatically teaching itself new reference points, and of using this capability to perform insertion operations in an adaptable manner.

3.0 SYSTEM CONFIGURATION

The system used to test the concepts is shown in Figure 2. The system elements were selected partly because of availability, and do not necessarily constitute our recommendations for a commercial implementation. For example, the algorithm can be run on a much smaller computer than a VAX 11/780. The PUMA robot, the manipulator and the vision system are all controlled and/or monitored by a microcomputer (a DEC DCT11-EM). The PUMA robot contains its own controller (LSI-11/2) and system software (VAL). The PUMA also has a digital I/O module that can be used to communicate with external devices. It is the digital I/O lines that the DCT11-EM uses to see if the robot has completed a motion, to signal the robot to proceed to next step, or to terminate the present move. The I/O lines are triggered or monitored through a parallel port on a data acquisition interface.

The end effector was designed specifically to aid the implementation of the visual servoing algorithm to be discussed. The end effector consists of an xy positioning wrist and a set of fingers whose tips contain a platform capable of rotating a part about an axis that is the common normal to the fingers. This rotational capability assists in acquiring the pin because acquisition is easier when the pin's long axis is perpendicular to the long axis of the fingers (see Figure 3). The fingers have force sensing capability along their long axis (the direction of insertion). A more detailed description of the end effector is given in Section 5.0.

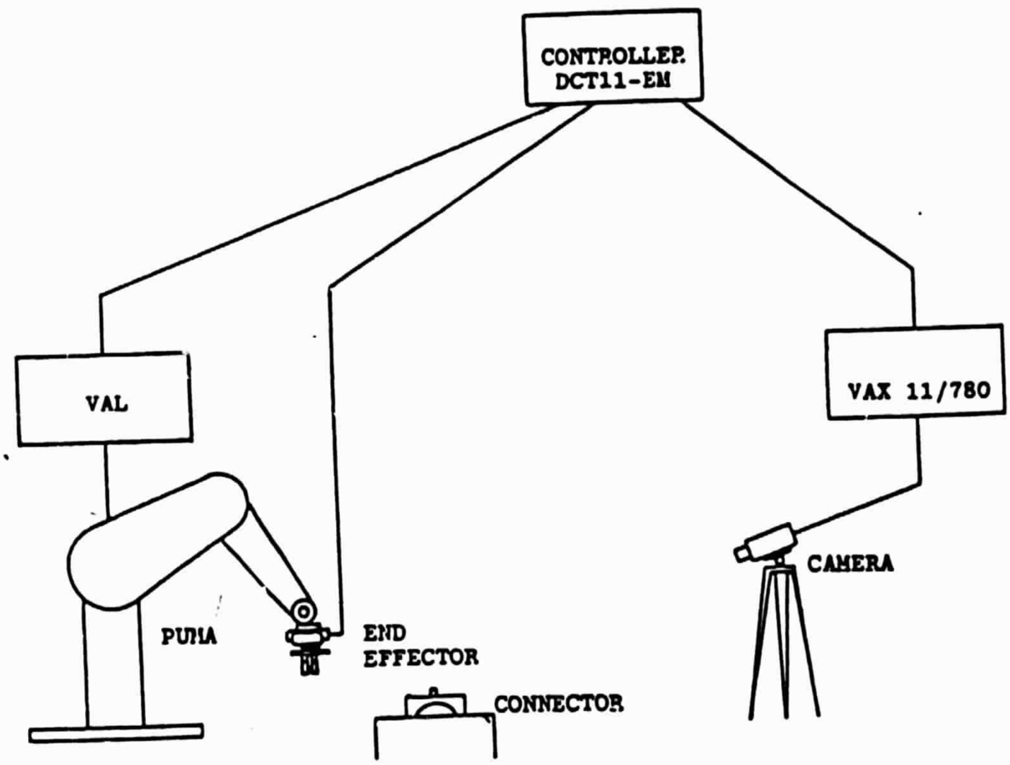


Figure 2. System Configuration

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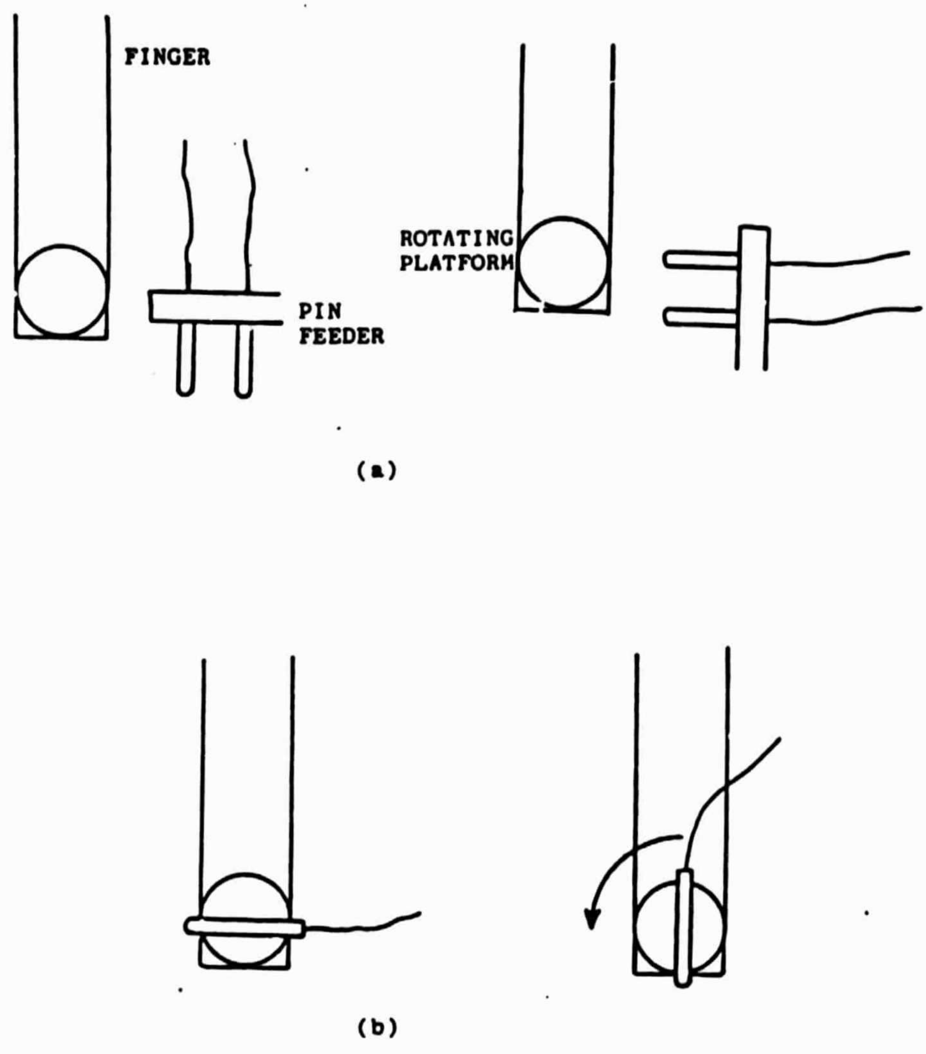


Figure 3. Pin Acquisition with a Rotating Platform on the Fingertips. (a) The wires do not interfere when the pins are fed horizontally. (b) The pin must be rotated to the vertical for the servoing process.

A Hitachi KP-120 CCTV camera interfaced to a VAX 11/780 is utilized for vision feedback to control the manipulating end effector. The Hitachi camera consists of a solid state pickup device with a resolution of 320 by 244 pixels. All communications between the vision routine in the VAX and the DCT11-EM are performed through the RS-232 port.

The connector where the insertions are to be performed is mounted into a simple fixture that holds it rigidly and vertically so that the top face of the connector is horizontal. The face of the connector used in our tests is 25mm in diameter and has thirteen holes 0.8 mm in diameter. However, our methods should be applicable to any connector that has holes for pin-type terminations.

Lighting conditions are provided by two lights, one to process the holes on the connector, the other to highlight the pin. The lighting setup is shown in Figure 4. The back light is used only when the connector is being analyzed for the hole locations. The front light is on at all times and reflects off the pin when being positioned. When the pin is being positioned the back light is switched off.

4.0 CONTROL ALGORITHMS

Visual servoing is utilized to position the robot in the vertical direction (y_w) and also to control the manipulating wrist in the horizontal directions (x_w and z_w).

4.1 Geometric Analysis

The target hole in the connector and the pin must both be in the image field of view, and this can be accomplished by mounting the camera off to one side of the connector stand and at an angle to the horizontal. Figure 4 shows the oblique mounting of the camera. Only two

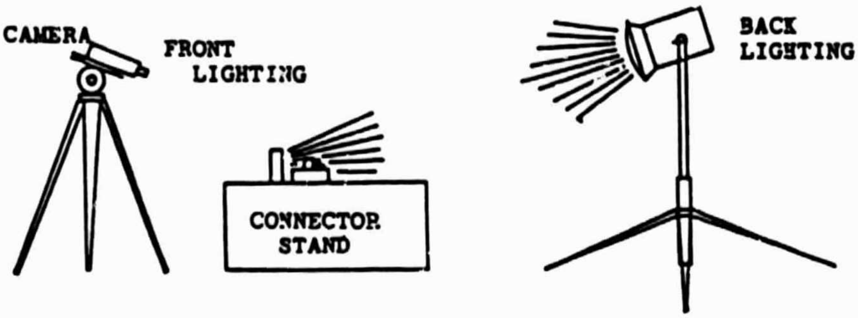


Figure 4. Lighting Arrangement

dimensional information can be extracted from a camera image. No depth information along the axis perpendicular to the camera image can be calculated. For a fixed camera placed at an angle to the surface the height of the pin over the hole in the image is related to the actual height of the image from the hole, the angle of the camera, and the magnification of the lens.

The acqusition of an image utilizing a camera can be mathematically modelled by replacing the lens with a pin hole. The pin hole camera is the simplest of all cameras. In theory only one ray from a point in space can pass through the infinitesimally small hole at the center where the lens is supposed to be. The xyz coordinate system used is located at the lens center, and is shown in Figure 5 (the x coordinate points into the page). Let the distance q be the fixed distance corresponding to the distance between the lens center and the image plane. The focal length is f. The coordinates of a point in the image plane are x_i and y_i (see Figure 5).

From similar triangles a point on an object at location (x,y,z) is related to the image coordinates x_i, y_i for a pin hole camera as

$$x_i = -qx/z \tag{1}$$

$$y_i = -qy/z \tag{2}$$

The above equations show that for a pin hole camera the position of the point in the image is related to the object's perpendicular distance away from the principal ray and the distance along the principal ray. For a camera placed at an angle from the horizontal a motion in the horizontal

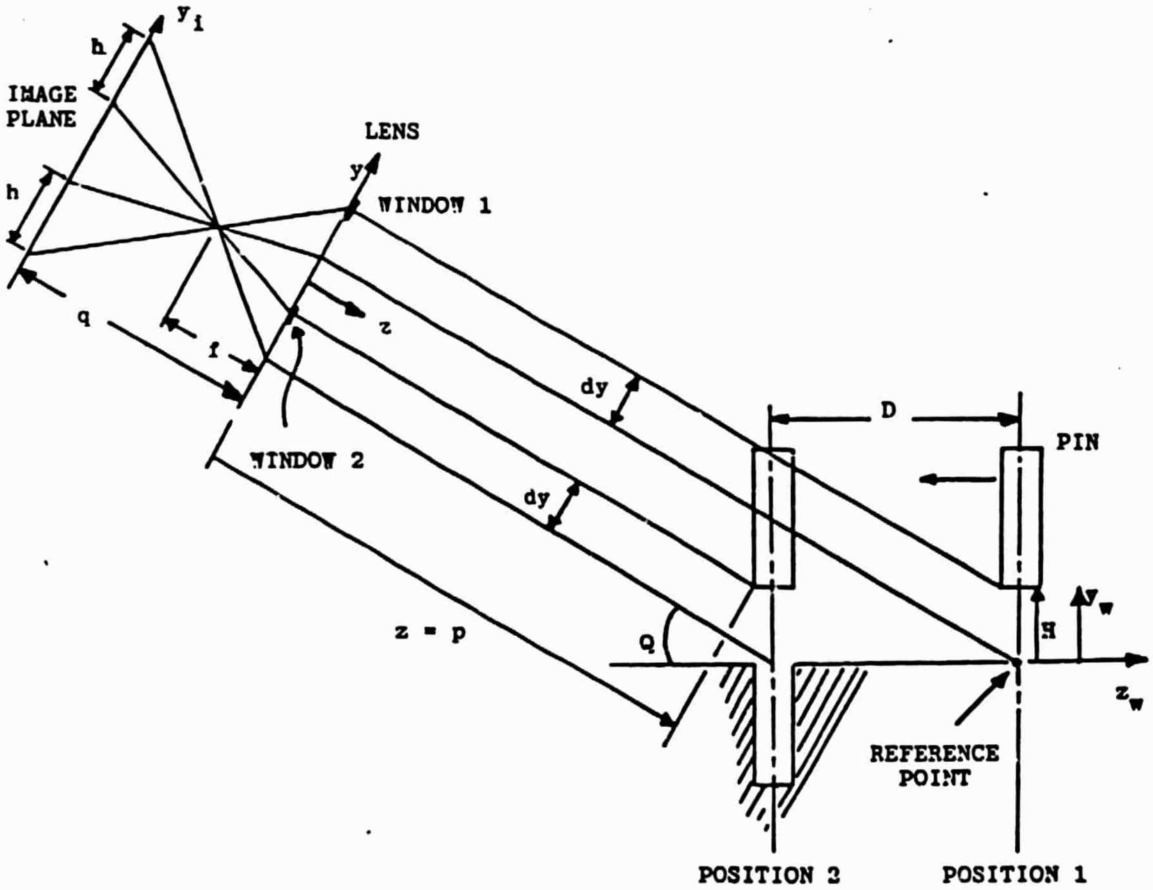


Figure 5. The Geometric Model

plane causes both a change in the distance of the object from the principal ray and a change in the distance along the principal ray.

For the experimental setup a lens with a 75 mm focal distance is used with a 10 mm extender. This makes the total required distance of the image from the lens 85 mm. From the lens equation $1/q+1/p = 1/f$ the distance p from the object to the lens is calculated to be 637.5 mm. This is the distance of the position of the connector from the lens along the principal ray of the camera (see Figure 5). The maximum horiontal distance of travel of a pin across the connector is 25mm, and the camera is mounted at about 30.0 degrees from horizontal (Q). For this geometry we can use a linearization of Equation (1) about the value $z = p$. Thus the change in the image coordinate y_i is approximately given by

$$dy_i = -q\ dy/p \tag{3}$$

The linearization of Equation (1) has the effect of eliminating the perspective transformation that normally will occur when using the pin hole camera model. With this linearization our camera model is described by the geometry of Figure 5. When the perspective transformation is not considered, the complexity of the vision analysis is greatly reduced. The following sections describe how a pin can be servoed using the linearized analysis so that it can be positioned above a hole.

4.2 <u>Horizontal Positioning</u>

Since q and p are constants, the change in y_i is linearly dependent on the change in the object's position in the direction perpendicular to the principal axis (y). If two locations, numbered 1 and 2 in Figure 5 are a distance D away from each other the change in position of the two

holes in the image will be given by dy_i. This is the same change that occurs for the motion of the pin a distance D. Therefore the height of the pin image above the hole image for position 1 is equal to the height of the pin image above the hole image for position 2. Therefore we position the pin above a reference point on the connector and move the pin horizontally (in the negative z_w direction), thus maintaining a constant pin height above the connector surface.

By keeping the height of the pin above the connector constant it is possible to calculate how far above the hole image the tip of the pin image must be so that the pin is aligned above the hole. From Figure 5:

dy = distance between pin and hole along the axis perpendicular to the principal ray

m = magnification factor of the lens
  = q/p

H = height of the pin above the hole in world coordinates (x_w, y_w, z_w)

h = height of the pin above the hole in image coordinates (x_i, y_i)

We wish to calculate h. From equation (3)

$$h = -q\ dy/p = -m\ dy$$

From trigonometric relationships

$$dy = H \cos (Q)$$

Therefore

$$h = -mH \cos (Q) \tag{4}$$

Variables dy_i and h, from equations (3) and (4) repectively, are along the y-axis of the camera. The x-axis of the camera is aligned parallel to the world x_w-axis and any motion in the world x_w-axis does not constitute a change in the position along the principal ray. Therefore from equation (1), $x_i = -qx/p$, and a change in the x direction (dx) causes a change in the camera coordinates of $dx_i = -(q/p)\ dx$. Thus the inherent nonlinear problems that occur when investigating the change in the y-axis of the image due to a positional change D are not present in the x direction.

Since calculations are done in pixel size and not in actual units of distance, a simple approach is to calibrate the camera by actually placing the pin directly above the hole at an arbitrary height and noting on the image what the difference is between the pin position and the hole center in pixels. When calibrated with this method the actual height H of the pin and the camera angle Q are not necessary.

4.3 Accomodating for Variable Pin Height

As discussed previously, one important factor for the insertion of pins into a connector for the assembly of wire harnesses is flexibility, since different types of connectors and matching pins have to be considered. Calibrating the camera for each assembly operation in the manner described above can be a very time consuming operation. Also, differing pin lengths and variability in grasp location mean that the pin tip will not always be at the same height above the connector surface

unless the control software can compensate for this variability. Figure 6 shows the error that can occur if the pin is not placed at the correct height above the hole.

The problem of variable pin height can be solved by placing the pin directly above a fixed reference point on the connector. This point's image location has been previously recorded. The pin is then servoed down towards the reference point until the tip of the pin in the image is at a predetermined pixel height above the image location of the reference point. This same pixel height is then utilized to position the pin above the desired hole for insertion. The pin is servoed towards the camera until it appears in the image above the hole at the same pixel height that was used with the reference point.

4.4 Establishing the Reference Point

To make the assembly operation less dependent on an operator it is possible to have the robot choose the reference point. It is assumed that the robot will have a general idea where the connector is located since in the overall wire harness assembly the connector could be placed in the vise by the robot. Initially the robot grasps a special pin with a small LED mounted on the end and facing the camera. This pin is wider than the holes in the connector so that it can not be inserted into any of the holes. The pin is lowered down towards the connector until the pin touches the connector surface (this is detected by the force sensor in the fingertips). At this point an image is taken of the LED and recorded. In this way the reference point can be positioned at the connector surface height, and this height is then known to the robot. In the manner described above, the pin is positioned above the reference point and servoed downwards until it appears at a predetermined pixel

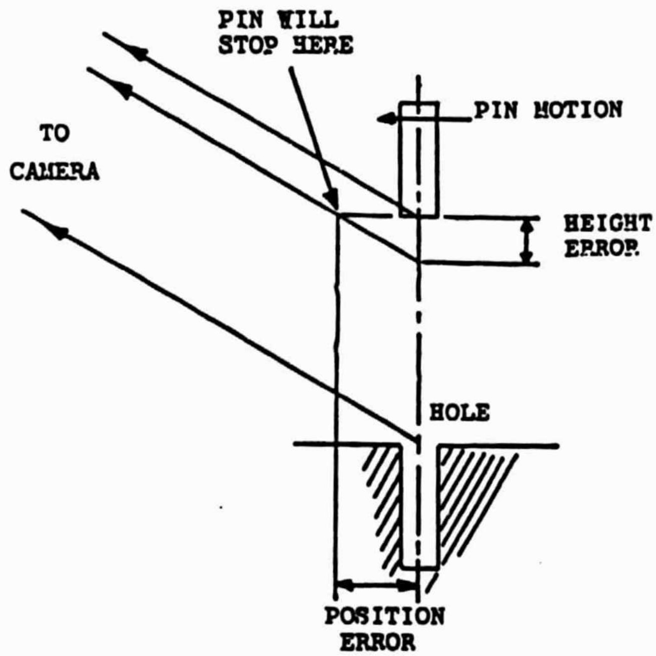


Figure 6. Positioning Error Due to Incorrect Pin Height

height above the reference point. Figure 7a shows the procedure as seen along the x axis. Figure 7b shows the view from the camera.

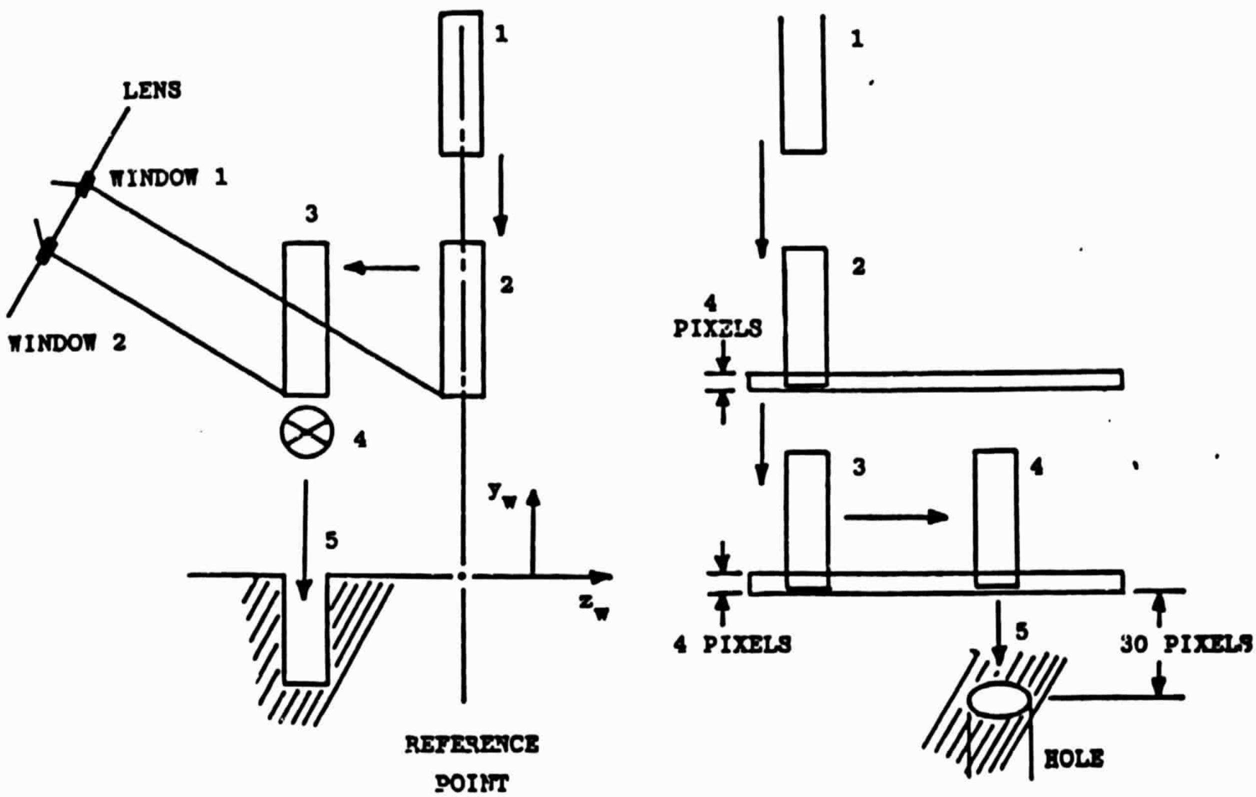
The visual analysis uses small window strips at two positions. These windows are 40 pixels longer than the connector window and four pixels high. Window strip 1 is placed 30 pixels above the recorded image location where the LED pin touched the connector surface. Window strip 2 is placed 30 pixels above the image location of the connector hole. These strips are shown in Figures 5 and 7. Initially, the pin tip is placed high enough so that it will not appear in either window. The pin is then moved down in the negative y_w direction until the pin enters window 1. Then the pin is moved forward in the negative z_w direction until it enters window 2. The pin then has the same z_w coordinate as the connector hole. At this point the pin is moved in the x_w direction, which coincides with the x direction.

For servoing along the x_w-axis it is assumed that the pin has already entered the image strip. The center of gravity of the pin in the x image direction is calculated and compared to the x coordinate of the hole image. When the two align the vision routine signals the microprocessor to stop the motors. The same routines that are utilized to find the center of gravity and bottom of the LED are used to locate the the pin tip and to see if there is a pin actually in the image.

4.5 Summary of the Procedure

The following steps constitute the procedure for the assumed scenario.

1. The robot places a connector in the fixture.



(a) Side view

(b) Camera view

Figure 7 . The Insertion Sequence

2. The robot acquires the LED pin and touches the surface of the connector. The image of this point is recorded. The connector height is now known in terms of a pixel location. This is reference point 1. Window strip 1 is placed 30 pixels above this point.
3. The robot replaces the LED pin and begins the insertion process. It acquires a new pin but does not know exactly how far this pin protrudes from the fingertips.
4. The end effector is moved to a point directly above reference point 1, at an end effector height high enough to allow the tip of the longest pin to be above window strip 1.
5. The robot then servos down until the pin tip enters window strip 1. The pin tip is now at a known height directly above reference point 1.
6. The robot servos the pin forward (toward the camera) until the pin tip enters window strip 2. The pin tip now has the same z_w coordinate as the connector hole.
7. The end effector servos the pin sideways (in the x_w direction) until the pin image lines up vertically with the hole image. The pin is now directly over the hole.
8. The robot servos the pin downward until the insertion detent force is detected by the force sensor.

5.0 DESIGN OF THE END EFFECTOR

From the above procedure we see that the following motions are required of the system:

1. Robot motions:
   a) acquisition of the pins and transportation to the general vicinity above the connector;

b) vertical motion (along the y_w direction)

2. End effector motions:

   a) fingertip grasp for holding the pin;

   b) platform rotation at the fingertips, for pin acquisition and vertical alignment (see Figure 3);

   c) horizontal translation in the z_w direction;

   d) horizontal translation in the x_w direction.

The end effector designed to implement these motions in an easily-controllable manner is shown in Figure 8. It has a wrist that consists of two sections. Each section has a motor-driven lead screw that provides a translation for whatever is connected below it. When the wrist is horizontal and facing the camera as shown in the lower left-hand drawing of Figure 8, the lead screws provide translations of the pin in the z_w and x_w directions, as required for the servoing algorithm.

The opening and closing of the fingers is pneumatically actuated in an on-off manner. The rotation of the fingertip platforms is produced with a motor driving a flexible shaft. Each fingertip contains a strain-gage sensor for measuring forces in the y_w direction.

6.0 DETERMINATION OF PIN ORIENTATION AT ACQUISITION

In addition to simplifying the pin acquisition process as shown in Figure 3, the rotating platforms on the fingertips can be used to determine the location and orientation of the pin when it is acquired. Figure 9 shows an arbitrary situation at acquisition. Two pairs of infrared through-beam sensors are mounted on the fingers at the rim of the rotating platform. The emitters are on one finger; the detectors on the other. With two pairs of such sensors, we can determine the pin

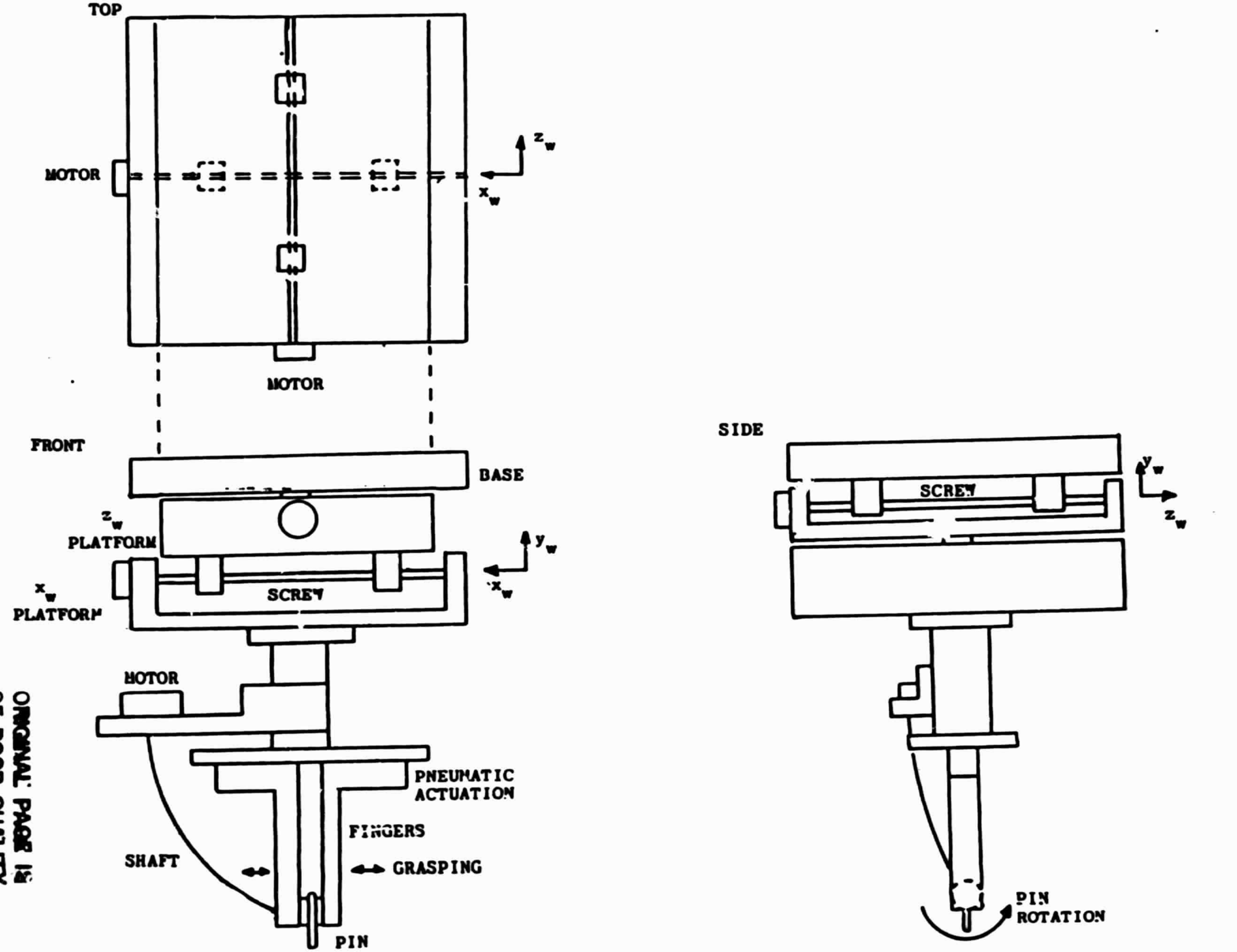


Figure 8. Three Views of the End Effector

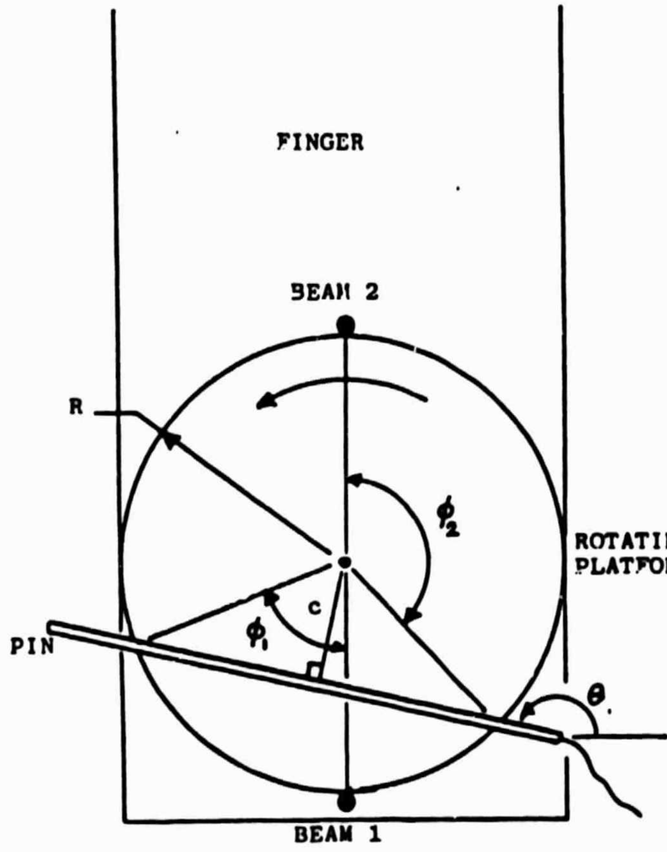


Figure 9. Determination of Pin Location (c, Θ) after Acquisition.

orientation by rotating the pin with the platform no more than 180°. The 180° limitation is due to the trailing wire on the back of the pin.

When the pin is acquired the platform is rotated counterclockwise. The stepper motor controller monitors the angular rotation needed to interrupt sensors 1 and 2; these angles are denoted ϕ_1 and ϕ_2. From trigonometry it can be shown that the pin's angular orientation θ and offset c are given by

$$\tan\theta = (C_1 + C_2)/(S_1 + S_2) \tag{5}$$

$$c = aR(S_1 - S_2)/b \tag{6}$$

where

$$S_i = \sin\phi_i \tag{7}$$

$$C_i = \cos\phi_i \tag{8}$$

$$a = \sqrt{2/(1+C_1C_2 - S_1S_2)} \tag{9}$$

$$b = 2(S_1S_2 - C_1C_2) \tag{10}$$

$$R = \text{platform radius} \tag{11}$$

The orientation θ is used to align the pin vertically prior to the servoing process shown in Figure 7. Because the center of the platform is initially aligned above reference point 1, the offset c would cause the pin to miss the hole by the distance c. But since c can be calculated from (6), we can compensate for its effect when the wrist moves in the z direction.

7.0 PERFORMANCE TESTING

This section describes the results of testing the control algorithm. The tests were performed at a pin height above the hole that corresponded to approximately 3mm above the connector. A series of pin positioning trial runs showed that the pin could be positioned above the desired hole. It was discovered that even if the pins were slightly off vertical there was enough compliance in the fingers to allow for insertion. However, the method is somewhat sensitive to lighting conditions.

The main use of the front light is to brighten the pin. The ideal lighting configuration is to have the light positioned so that the majority of the light is reflected off of the pin and into the camera. Unfortunately, if the light is positioned below the connector to achieve total reflection into the camera, if the pin moves near the back of the connector the light is blocked by the connector itself.

The optimum configuration is to have the light tilted about 10° above horizontal. If the pin is not rotated but kept vertical, the light that is reflected into the camera is diffused lighting from the pin, which lowers the intensity of the pin in the image. If not enough light is reflected off the pin into the camera, the pin will blend into the background.

The type of pin that was used for the assembly was a silver color pin about 25 mm long. With this type of pin it was possible to obtain enough contrast. No detailed study was done on the reflectivity of different types of pins but in general gold pins do not tend to be as bright as the silver pin that was used in the experiment.

8.0 CONCLUSIONS

The performance characteristics that were desired were:

1. Accurate positioning of the pin over the desired hole for insertion.
2. Flexibility in the system so that different pins and uncertainties in grasp location can be easily accomodated.

The performance tests show that the robotic assembly of pins into a connector in a flexible but accurate manner is feasible. It was shown that with the use of visual feedback from one camera a pin of any length can be acquired and positioned accurately enough over the desired hole for insertion. With the combination of force feedback the procedure can be automated such that the robot itself can locate a reference point on the connector. This eliminates the need for an operator to teach the robot a reference point every time a different assembly is started.

It was shown that, by using a vision algorithm that relies upon the relative distance between where the pin is and where it should be, costly set up times could be eliminated since the camera need not be calibrated to the robot frame. The elimination of camera calibration is very important for an operation where changes are to be made often in the assembly operation.

The success of the control algorithm is due partly to the design of an end effector that easily gives the motions required by the control algorithm; namely, accurate horizontal translation in two directions across the connectors' surface, and rotation at the fingertips to ease pin acquisition and to optimize light reflection off the pin.

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